LINE DIAGNOSTICS FOR Ne V AND Mg V SOLAR IONS

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Abstract. Spectroscopic diagnostics for the Ne V and Mg V solar ions have been investigated. The theoretical forbidden line ratios from these ions are presented for estimating the Ne/Mg variation in different solar structures. Calculations for density and temperature line diagnostics of these ions are given for the several spectral line ratios and their applications are discussed with the help of available solar observations in space. Future observations from the CDS and the SUMER experiments aboard the SOHO satellite are also discussed.

1. Introduction

Access to the EUV and X-ray images and spectra, and their interpretations, have greatly improved our understanding of the very complex nature of the solar atmosphere and the underlying physics. The inference of plasma densities, temperatures and their inhomogeneities through spectroscopic diagnostics for solar ions, is a problem of universal importance for both laboratory and cosmic plasmas (Dwivedi, 1994). Evidence, however, mounts that elemental abundances in the corona differ from their photospheric values (Meyer, 1985). This variation can affect temperatures, densities and emission measures derived from spectroscopic diagnostics, which will result in incorrect estimates of energy budgets, cooling times and relative amounts of emission in different spectral bands. The element abundances seem to vary depending on the first ionisation potential (FIP) of the element. Elements with high FIPs are less abundant relative to elements with low FIPs in the corona than in the photosphere. The overabundance factor may vary from structure to structure (Feldman, 1992). If the FIP correlation exists, a large variation in the element abundance ratio Ne/Mg can be expected since neon is a high-FIP element, while magnesium a low-FIP one. Based on a study by Doschek and Bhatia (1990), it has been proposed to investigate the upper transition-region abundance variations (and also electron densities) by measuring the intensity ratio of Ne V 1574.67 Å and Mg V 1324.45 Å forbidden lines from the SUMER experiment aboard the SOHO satellite (Wilhelm, 1994). Density and temperature diagnostics for the Ne V ion have been investigated previously (Raju and Dwivedi, 1979; Keenan *et al.*, 1992). Shure *et al.* (1983) reported observations of the Ne V 24.28 μm infrared line from three planetary nebulae and used their line fluxes to obtain Ne V abundances for these nebulae. They also measured the 24.28 μm/λ3426 Å line ratio to estimate an electron temperature for NGC 7662. Johnson, Kingston, and Dufton (1984) re-interpreted these observations and suggested the λ14.3 μm/λ3426 Å line ratio

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to be a good temperature diagnostic for electron densities $< 10^4$ cm^{-3}. The Mg V ion, however, has received little attention except a theoretical study by Raju and Dwivedi (1978). Several EUV lines of Ne V and Mg V ions have recently been observed from the Solar EUV Rocket Telescope and Spectrograph (SERTS) by Thomas and Neupert (1994). Furthermore, the EUV spectrum of different solar structures at greater spectral, spatial and temporal resolution, will be available from the CDS and the SUMER experiments aboard the SOHO satellite. In view of its prime importance with regard to diagnostic applications, we have carried out a detailed spectroscopic analysis for Ne V and Mg V ions using the most appropriate atomic data presently available.

In the following section, line diagnostics analysis is given. The energy level model and the atomic data used are discussed in Section 3. We present results and discussion in Section 4.

2. Line Diagnostics Analysis

The power (erg s^{-1}) emitted in an optically thin spectral line issued from a transition between an upper level (u) and a lower level (l) is given by

$$P(\lambda) = \frac{hc}{\lambda} A_{ul} \int_V N_u \, \mathrm{d}V \; , \tag{1}$$

where N_u is the number density and V is the volume of the emitting plasma. N_u can be further parametrized as

$$N_u = \frac{N_u(X^{+p})}{N(X^{+p})} \frac{N(X^{+p})}{N(X)} \frac{N(X)}{N(\mathrm{H})} \frac{N(\mathrm{H})}{N_e} N_e \; , \tag{2}$$

where $N(X)/N(\mathrm{H})$ is the abundance of the element X relative to hydrogen which may or may not be constant in the solar atmosphere; $N(\mathrm{H})/N_e$ is the hydrogen abundance which is usually assumed to be around 0.8 for a fully ionised plasma.

Combining Equations (1) and (2) and removing the mean values of atomic parameters from the integral, we can write

$$P(\lambda) = 0.8 \frac{hc}{\lambda} A_{ul} \frac{N(X)}{N(\mathrm{H})} \left(\beta \frac{N(X^{+p})}{N(X)} \right) \frac{N_u(X^{+p})}{N(X^{+p})} N_e V \; , \tag{3}$$

where $N(X^{+p})/N(X)$ is evaluated at the temperature of maximum ion abundance, the factor β expresses the fact that the average value of $N(X^{+p})/N(X)$ is less than the maximum value, and $N_u(X^{+p})/N(X^{+p})$ is evaluated at the electron density corresponding to the temperature at which the contribution function is maximum.

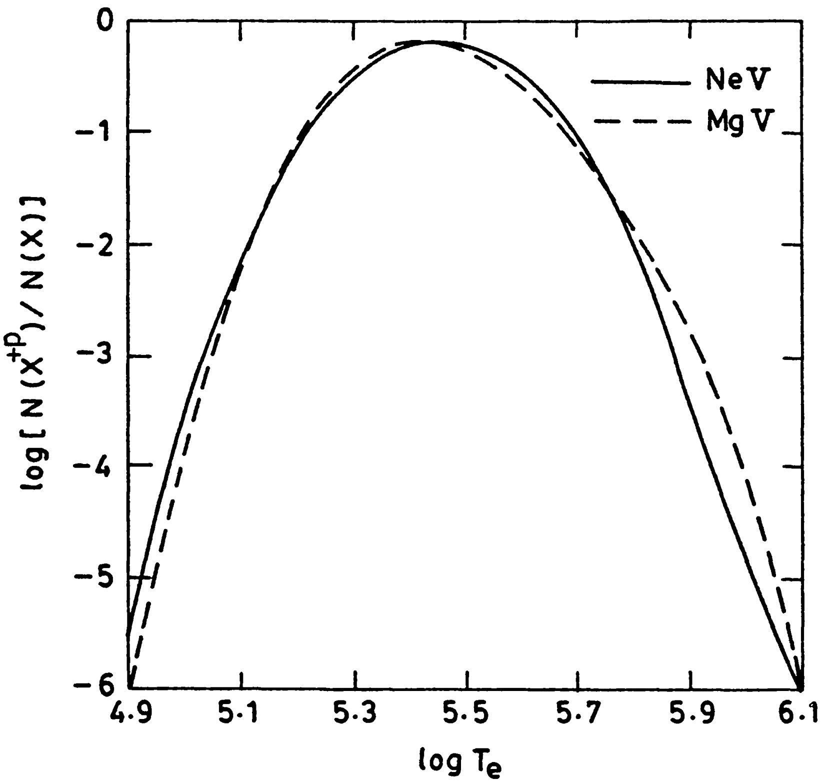

Fig. 1. Ionization equilibrium curves for Ne V and Mg V ions (from Arnaud and Rothenflug, 1985).

Following Jordan and Wilson (1971), β is evaluated from the average value of the contribution function over a constant logarithmic temperature width (= 0.3 dex) around the peak temperature of formation of the line. Because contribution functions for Ne V and Mg V ions have the same temperature width, it is not necessary to evaluate β for them. Using the ionisation equilibrium calculations of Arnaud and Rothenflug (1985) shown in Figure 1, we find the ion abundance fraction for Ne V and Mg V ions to be the same, namely 0.64.

In order to obtain relative abundances of elements X and Y, ratios of respective spectral line intensities are used. The line intensity ratio R of two lines, or ratio of the power in the lines, is qiven by

$$R = \frac{\lambda_{kl}}{\lambda_{ij}} \frac{A_{ji}}{A_{lk}} \frac{\beta_1}{\beta_2} \frac{N_j(X^{+p})/N(X^{+p})}{N_l(Y^{+q})/N(Y^{+q})} \frac{N(X^{+p})/N(X)}{N(Y^{+q})/N(Y)} \times$$

$$\times \frac{N(X)/N(\mathrm{H})}{N(Y)/N(\mathrm{H})} \frac{(N_e V)_1}{(N_e V)_2} \,. \tag{4}$$

If the intensity or power of the two lines has essentially the same temperature dependence (same contribution function), then the lines are formed presumably in the same plasma volume and at the same density, and the quantities N_e and V are the same for each line and drop out of Equation (4). This is the case for the Ne V and Mg V combination.

3. Energy Level Model and Atomic Data

The atomic model comprising the first 15 levels of the Ne V ion is considered. The ground configuration $2p^2$ causes ^3P, ^1D, and ^1S; the higher configuration $2s2p^3$ forms $^5S^0$, $^3D^0$, $^3P^0$, $^1D^0$, $^3S^0$, and $^1P^0$. For the Mg V ion, the first 9 levels are ^3P, ^1D, and ^1S from the ground configuration and $^3P^0$ and $^1P^0$ from the higher configuration. The wavelengths for the different transitions together with observed line intensities for Ne V and Mg V ions are listed in Table I. The transition probabilities and the wavelengths for the forbidden transitions of the Ne V ion have been taken from Nussbaumer and Rusca (1979). The wavelengths for the allowed transitions have been taken from the tabulation of Kelly and Palumbo (1973). For the reasons discussed by Burgess, Mason, and Tully (1991), in the case of forbidden transitions, the collision strengths for Ne V have been taken from Aggarwal (1984). For allowed transitions, we have used the Bhatia and Doschek (1993) values of collision strengths and the transition probabilities. We have also taken account of proton excitation for the $^3P_0 -^3 P_2$ and $^3P_1 -^3 P_2$ transitions and photo-excitation for the $^3P_0 -^3 P_1$ and $^3P_1 -^3 P_2$ transitions.

The atomic data for Mg V have been taken from various sources. Allowed transition probabilities have been taken from Safronova (1975) and forbidden ones from Wiese, Smith and Miles (1969). Wavelength values are mainly from Kelly and Palumbo (1973). Collision strengths for the forbidden transitions have been taken from Lang and Summers (1994) and these have been estimated for the other fine structure transitions making use of the following relations:

$$\Omega(^1S,\, ^3P_J) = \tfrac{1}{9}(2J+1)\Omega(^1S,\, ^3P)\ ,$$

$$\Omega(^1D,\, ^3P_J) = \tfrac{1}{9}(2J+1)\Omega(^1D,\, ^3P)\ ,$$

given by Saraph, Seaton, and Shemming (1969). We did not find collision strengths for the allowed transitions in the literature. However, these values are listed for Si VII, S IX and Ar IX of the same sequence as Mg V for a range of temperatures (Lang and Summers, 1994). One can crudely estimate the corresponding values for collision strengths by extrapolation along the ions of the oxygen sequence. While atomic data are needed for detailed spectroscopic diagnostics for the Mg V ion, we have estimated these by scaling along the iso-electronic sequence, namely by multiplying the collision strengths for Si VII by a factor Z^2(Si VII)/Z^2(Mg V), where Z is the residual charge on the ion.

4. Results and Discussion

Solar wind studies and spectroscopic investigations reveal the variation of relative solar element abundances in different regions of the solar atmosphere. Understanding the causes of these variations and measuring accurate element abundances in

TABLE I

Ne V and Mg V lines and their observations

Transition	Wavelength (Å)	Intensity (erg cm^{-2} s^{-1} sr^{-1})		
		Ne V		
$2s\,2p^3\,{}^3S_1^0 - 2s^2\,2p^2\,{}^3P_1$	358.45	15[a]		
$2s\,2p^3\,{}^3S_1^0 - 2s^2\,2p^2\,{}^3P_2$	359.37	26.3[a]	168[b]	2750[c]
$2s\,2p^3\,{}^1P_1^0 - 2s^2\,2p^2\,{}^1D_2$	365.61		(120[blend])[b]	
$2s\,2p^3\,{}^1D_2^0 - 2s^2\,2p^2\,{}^1D_2$	416.20	24.2[a]	92[b]	1970[c]
$2s\,2p^3\,{}^1P_1^0 - 2s^2\,2p^2\,{}^1S_0$	416.82		14[b]	
$2s\,2p^3\,{}^3P_1^0 - 2s^2\,2p^2\,{}^3P_0$	480.49	24[b]	135[c]	
$2s\,2p^3\,{}^3P_1^0 - 2s^2\,2p^2\,{}^3P_1$ $2s\,2p^3\,{}^3P_2^0 - 2s^2\,2p^2\,{}^3P_1$	481.38	39[b]	331[c]	
$2s\,2p^3\,{}^3P_2^0 - 2s^2\,2p^2\,{}^3P_2$ $2s\,2p^3\,{}^3P_1^0 - 2s^2\,2p^2\,{}^3P_2$	482.98	64[b]	583[c]	
$2s\,2p^3\,{}^3D_1^0 - 2s^2\,2p^2\,{}^3P_0$	568.35	(33[blend])[b]	172[c]	
$2s\,2p^3\,{}^3D_2^0 - 2s^2\,2p^2\,{}^3P_1$	569.77	67[b]	480[c]	
$2s\,2p^3\,{}^3D_3^0 - 2s^2\,2p^2\,{}^3P_2$	572.29	81[b]	637[c]	
$2s\,2p^3\,{}^5S_2^0 - 2s^2\,2p^2\,{}^3P_1$	1136.60			
$2s\,2p^3\,{}^5S_2^0 - 2s^2\,2p^2\,{}^3P_2$	1145.61			
$2s^2\,2p^2\,{}^1S_0 - 2s^2\,2p^2\,{}^3P_1$	1574.67			
$2s^2\,2p^2\,{}^1D_2 - 2s^2\,2p^2\,{}^3P_2$	3426.84			
$2s^2\,2p^2\,{}^3P_1 - 2s^2\,2p^2\,{}^3P_0$	24.28 μm			
$2s^2\,2p^2\,{}^3P_2 - 2s^2\,2p^2\,{}^3P_1$	14.34 μm			
		Mg V		
$2s\,2p^5\,{}^1P_1^0 - 2s^2\,2p^4\,{}^1D_2$	276.58	31.6[a]		
$2s\,2p^5\,{}^3P_1^0 - 2s^2\,2p^4\,{}^3P_2$	351.11	13.11[a]		
$2s\,2p^5\,{}^3P_0^0 - 2s^2\,2p^4\,{}^3P_1$	352.20			
$2s\,2p^5\,{}^3P_2^0 - 2s^2\,2p^4\,{}^3P_2$	353.08	10.4[a]		
$2s\,2p^5\,{}^3P_1^0 - 2s^2\,2p^4\,{}^3P_1$	353.30			
$2s\,2p^5\,{}^3P_1^0 - 2s^2\,2p^4\,{}^3P_0$	354.16	7.7[a]		
$2s^2\,2p^5\,{}^3P_2^0 - 2s^2\,2p^4\,{}^3P_1$	355.33	11.9[a]		
$2s^2\,2p^4\,{}^1S_0 - 2s^2\,2p^4\,{}^3P_1$	1324.45			
$2s^2\,2p^4\,{}^1D_2 - 2s^2\,2p^4\,{}^3P_2$	2784.03			

[a] Thomas and Neupert (1994).
[b] Widing, Feldman, and Bhatia (1986).
[c] Noyes *et al.* (1985).

different solar regions is critical for solar physical processes and also important for astrophysics in general. Keeping in view its crucial role in coronal physics, an observing sequence (Wilhelm, 1994) is proposed to investigate the upper tran-

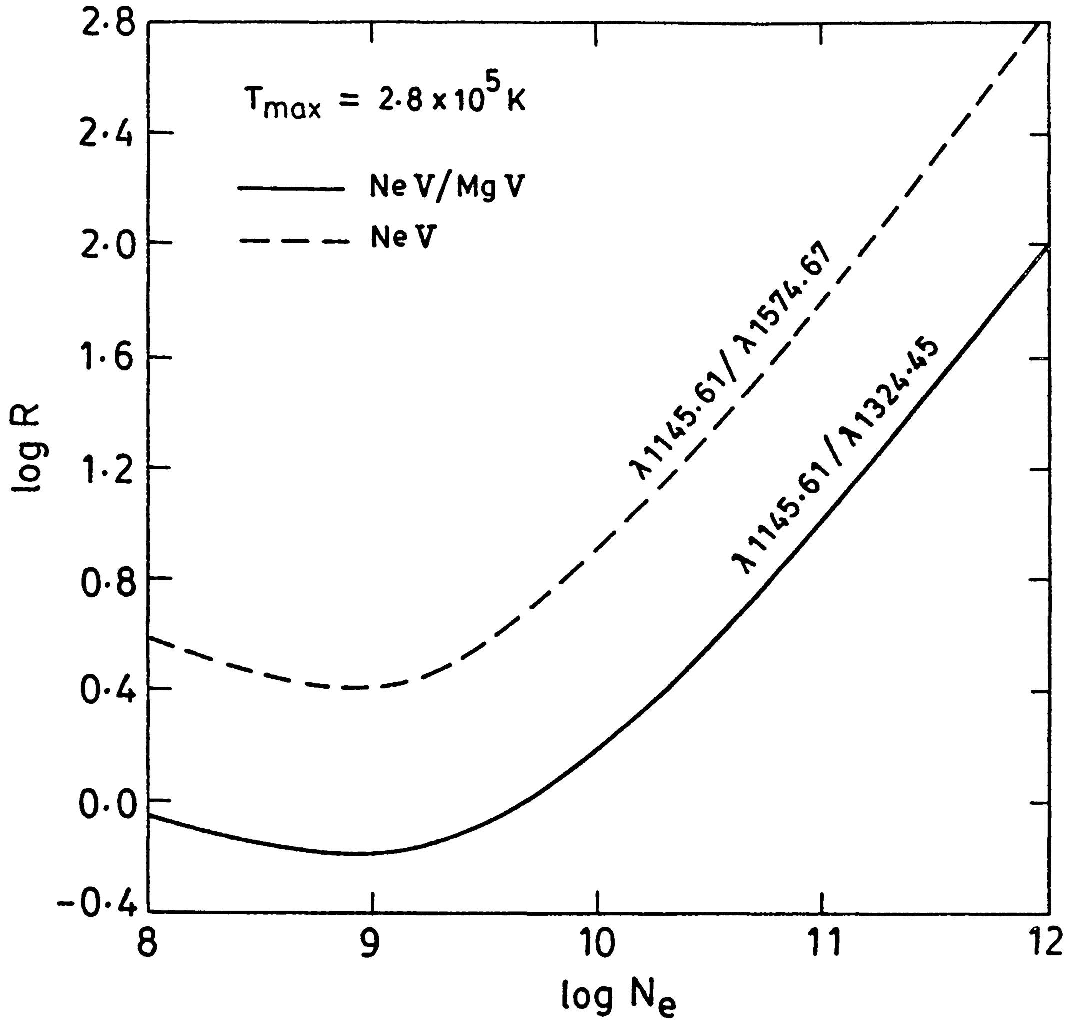

Fig. 2. Ne V (broken line) and Ne V/Mg V (solid line) theoretical line ratio curves at $T_{max} = 2.8 \times 10^5$ K as a function of electron density.

sition region abundance variations (and also electron densities) by measuring the intensity ratio of the high FIP spectral line of the Ne V ion at 1145.61 Å to a low FIP spectral line of the Mg V ion at 1324.45 Å formed at nearly the same temperature (cf., Figure 1) in ionisation equilibrium. That is, their contribution functions (product of the fractional ion abundance and the excitation rate for the spectral line considered) are nearly identical. This means that the emission measure of the solar plasma has no effect on ratios of Ne V and Mg V lines. Ions such as Ne V and Mg V are, therefore, most suitable for determining element abundance ratios. In addition, observations of another Ne V line at 1574.67 Å are needed to estimate electron density from the Ne V λ1145.61/λ1574.67 density-sensitive line ratio. This sequence will probably work best for pointing at active regions, quiet regions, coronal holes, and prominences off-limb, because of the weakness of the forbidden lines. The goal is to measure the forbidden lines in several different regions over a range of positions outside the limb, covering as large a range of heights as the counting rates allow.

Figure 2 shows the Ne V $\lambda 1145.61/\lambda 1574.67$ density-sensitive line ratio and the Ne V/Mg V $\lambda 1145.61/\lambda 1324.45$ line ratio (drawn for equal element abundances of Ne and Mg) as a function of electron density at $T_{\max} = 2.8 \times 10^5$ K. The Ne V 1574.67 Å line and the Mg V 1324.45 Å line have been discussed by Doschek and Bhatia (1990) because these lines were accessible to observation. Furthermore, the Ne V line was actually not observed in the S082-B *Skylab* spectra; it was too weak to be seen in the best *Skylab* forbidden line spectrum. However, the Ne V $\lambda 1574.67$ line is clearly seen in the spectrum of RR Tel observed by the International Ultraviolet Explorer (IUE) by Penston *et al.* (1983), so its wavelength is well known. The other Ne V line has been observed in the solar spectra discussed by Feldman and Doschek (1991). The ratio of the two forbidden lines of the Ne V ion is density-sensitive for $N_e > 10^9$ cm^{-3} (cf., Figure 2) while Bhatia and Doschek (1993) find this ratio to be useful for density measurement for densities less than about 3×10^{11} cm^{-3}. Furthermore, Doschek and Bhatia (1990) suggest the Ne V/Mg V $\lambda 1574.67/\lambda 1324.45$ line ratio for an element abundance ratio. This ratio shows a density variation by a factor of 2 in the relevant density range (10^9 to 10^{10} cm^{-3}). It will indeed be worthwhile to observe and interpret the Ne V/Mg V $\lambda 1145.61/\lambda 1324.45$ line ratio (cf., Figure 2) which is density-dependent for $N_e > 10^9$ cm^{-3} for studying the Ne/Mg variations in different solar structures. Thus the density obtained from the two Ne V lines will be useful in evaluating the Ne V/Mg V abundance ratio using the Ne V/Mg V line intensity ratio in different solar structures, e.g., in prominences and in open field regions, etc.

In Figure 3, we have plotted the Ne V to Mg V line ratios as a function of electron density at $T_{\max} = 2.8 \times 10^5$ K. Also plotted on the theoretical curves are the SERTS observations of an active region EUV spectrum together with error limits in the observed values. These line intensity ratios are dependent, in addition, on the relative element abundances. Theoretical line ratio curves of Figure 3 are drawn for equal element abundances of Ne and Mg, which means these line ratio curves are the normalized values given by the expression

$$R^* = \left\{ \frac{P(\lambda(\mathrm{Ne\,V}))}{P(\lambda(\mathrm{Mg\,V}))} \right\}^{\text{normalized}} =$$

$$= \left\{ \frac{P(\lambda(\mathrm{Ne\,V}))}{P(\lambda(\mathrm{Mg\,V}))} \right\}^{\text{actual}} \Big/ \left\{ \frac{N(\mathrm{Ne})}{N(\mathrm{H})} \Big/ \frac{N(\mathrm{Mg})}{N(\mathrm{H})} \right\} .$$

Element abundance of Ne and Mg with respect to hydrogen are 3.5×10^{-5} and 3.7×10^{-5}, respectively (Meyer, 1985). Widing and Feldman (1989) report a value of 0.64 in the active region for Ne/Mg abundance ratio and its variation from 0.8 to 1.5 in active region loops and flare loops. Using an average value of 0.8 and 1.5, which means Ne/Mg=1.15, which may be a reasonable value for the active

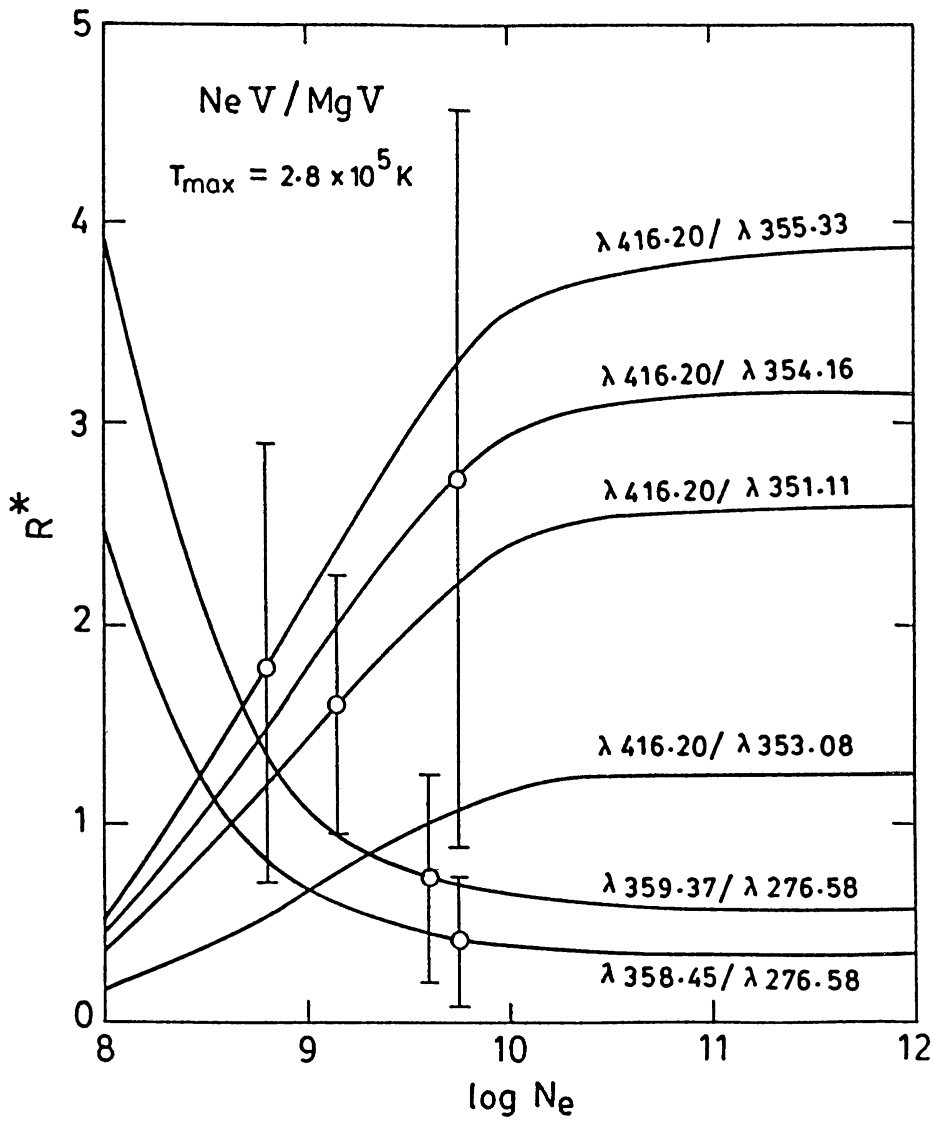

Fig. 3. Ne V/Mg V theoretical line ratio curves at $T_{\rm max} = 2.8 \times 10^5$ K as a function of electron density. The SERTS-observed line intensity ratios in the active region spectrum are shown by circles and error bars assuming Ne/Mg=1.15.

region (not completely representative of non-flaring active regions) and the SERTS observation (cf., Table I), we have estimated electron densities from Ne V/Mg V theoretical line ratio curves at $T_{\rm max} = 2.8 \times 10^5$ K (cf., Figure 3) and presented them in Table II.

Figures 4(a) and 4(b) show Ne V density-sensitive line ratios at $T_{\rm max} = 2.8 \times 10^5$ K. The circles and error bars in Figure 4(a) refer to the line intensity ratios in the active region spectrum observed by SERTS. We find definitely a low density of about 5.6×10^8 cm^{-3} in the active region (e.g., $N_e T_e = 1.6 \times 10^{14}$ cm^{-3} K) from the Ne V λ416.20/λ358.45 and λ416.20/λ359.37 line ratios (cf., Figure 4(a)). In Figure 4(b), we have plotted several density-dependent ratios for resolved line components of the Ne V ion which will be useful in the density measurements from

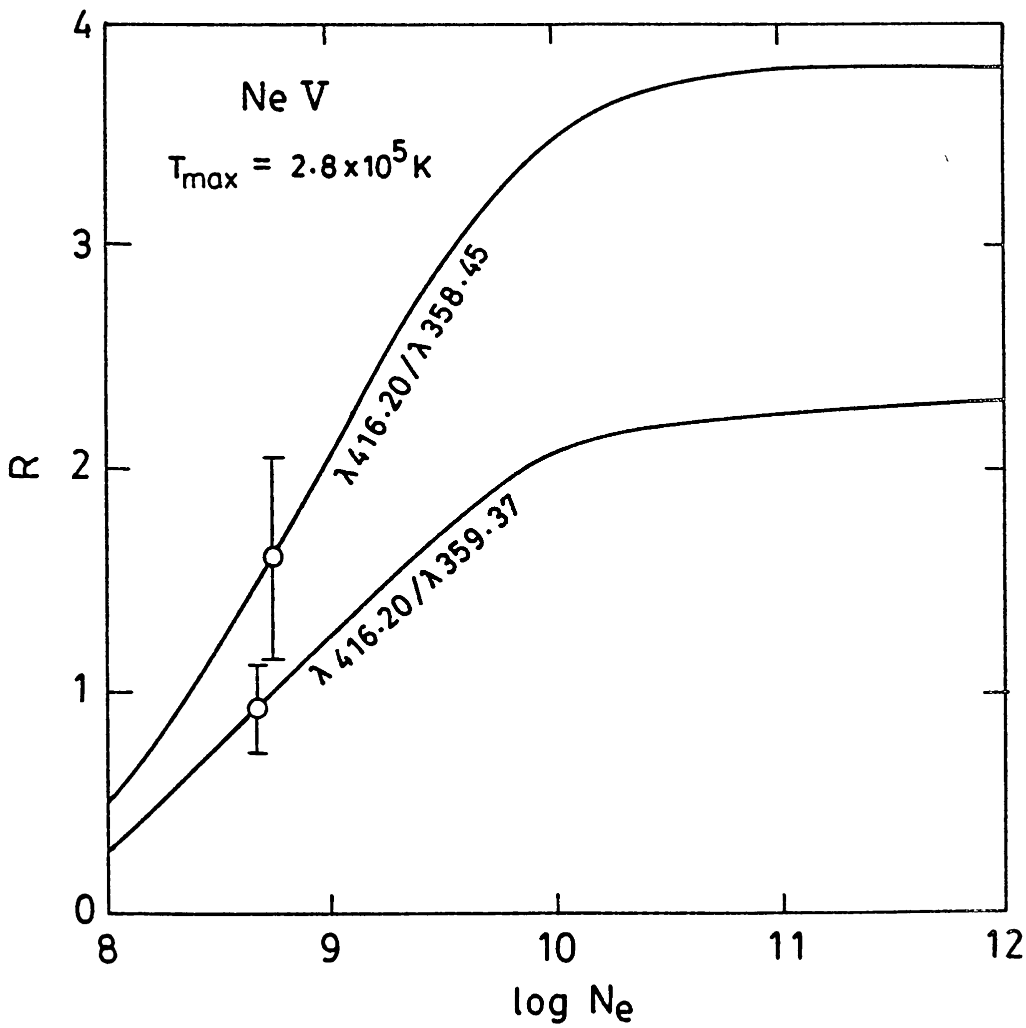

Fig. 4a. Ne V theoretical line ratio curves at $T_{max} = 2.8 \times 10^5$ K as a function of electron density. The SERTS-observed line intensity ratios in the active region spectrum are shown by circles and error bars.

TABLE II

Electron densities inferred from Ne V/Mg V line ratios at $T_{max} = 2.8 \times 10^5$ K (cf., Figure 3)

Line pair (Å)	Normalized observed line intensity ratio R^*	Inferred density N_e (cm^{-3})	$N_e T_e$ (cm^{-3} K)
λ416.20/λ355.33	1.8	6.3×10^8	1.8×10^{14}
λ416.20/λ354.16	2.73	5.6×10^9	1.6×10^{15}
λ416.20/λ351.11	1.6	1.4×10^9	3.9×10^{14}
λ416.20/λ353.08	2.02	–	–
λ359.37/λ276.58	0.72	4×10^9	1.1×10^{15}
λ358.45/λ276.58	0.41	5.6×10^9	1.6×10^{15}

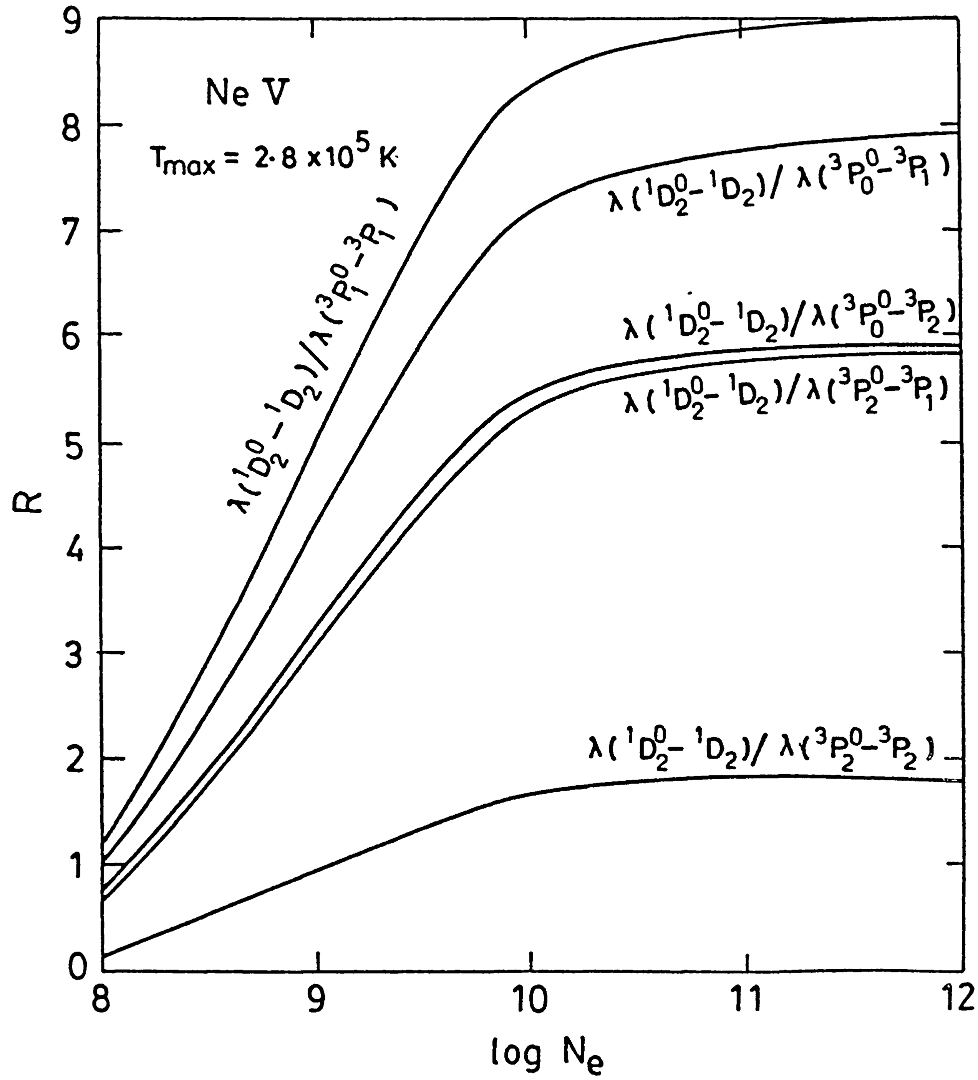

Fig. 4b. Density-sensitive Ne V theoretical ratios for resolved line components at $T_{\max} = 2.8 \times 10^5$ K.

the observations which will become available from the CDS experiment aboard the SOHO satellite (Harrison, 1993). It is to be further noted that some of these lines are observed (cf., Table I) in an erupting prominence (Widing, Feldman, and Bhatia, 1986) and in sunspot plumes (Noyes *et al.*, 1985) etc. However, poor spectral resolution of the ATM instruments aboard *Skylab* has been a major handicap to ascertain the line identifications and their intensities beyond doubt.

In Figure 5, we have plotted the Ne V temperature-sensitive line ratios $\lambda 572.29/\lambda 416.20$ and $\lambda 569.77/\lambda 416.20$ at $N_e = 10^{10}$ cm^{-3}. Also plotted on these curves are the observation of an erupting prominence by Widing, Feldman, and Bhatia (1986) together with error limits in the observed value. We have also shown by broken lines the results by Keenan *et al.* (1992) in this figure for comparison.

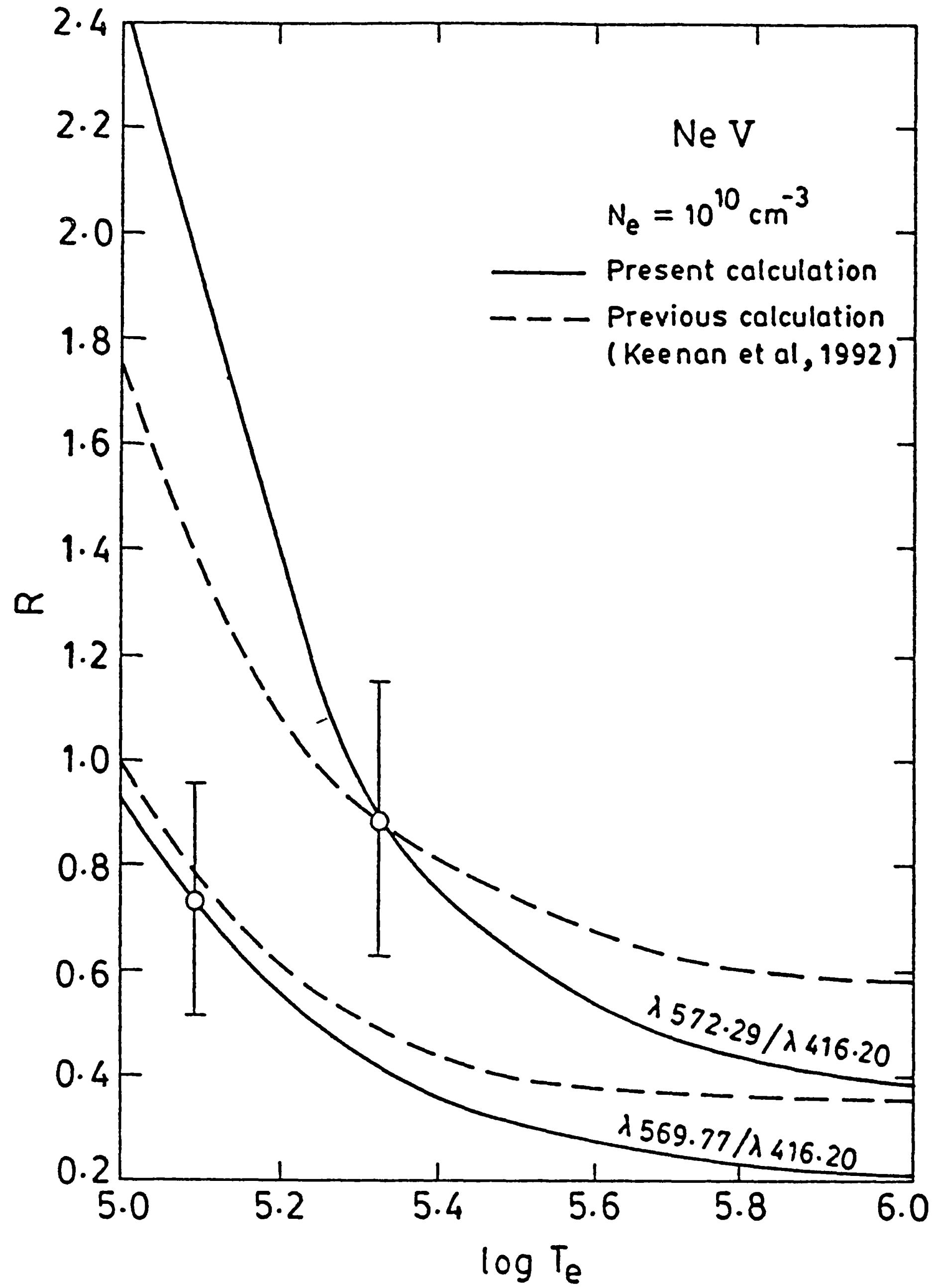

Fig. 5. Temperature-sensitive Ne V theoretical line ratio curves at $N = 10^{10}$ cm^{-3}. The observed line intensity ratios given by Widing, Feldman, and Bhatia (1986) in an erupting prominence are shown by circles and error bars.

5. Conclusions

In conclusion, we note that the EUV forbidden line spectra for the Ne V and Mg V ions are very valuable in diagnosing solar plasma and understanding the Ne/Mg variation in different structures. Allowed transitions of Ne V/Mg V line pairs are also good tools for diagnostic studies. In addition, Ne V line ratios are useful for temperature measurements of the emitting source. We also emphasize the need for atomic data calculations for the Mg V ion. The EUV spectrum of various solar features, which will be obtained at an excellent temporal, spatial and spectral resolutions by the CDS and the SUMER instruments to be flown on board the SOHO mission, will provide a rich source of data for interpreting the source in much finer details than that presently available.

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